FLOORS
Florida Object Oriented Reliability Simulator

Mark Law

Nicole Rowsey

David Horton

Michelle Griglione

Erin Patrick

Outline

- Introduction
- Off State Degradation Work
- On State Degradation Work
- Proton Effects
- Conclusion

FLOOPS / FLOODS / FLOORS

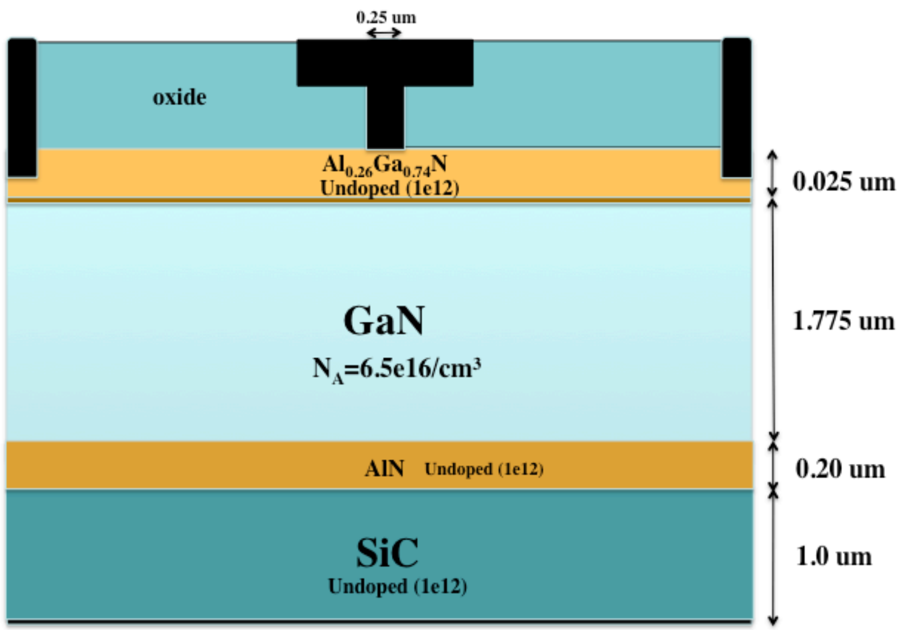
- Multi-dimensional
- P = Process / D = Device / R = Reliability
- 100% code shared, difference in startup scripts
- Scripting capability for PDE's - Alagator
- Commercialized - Synopsys
  - Sentaurus - Process is based on FLOOPS
  - Sentaurus – Reliability based on FLOORS
- Licensed at over 300 sites world-wide
  - 2008 release, planned 2012 release
  - Manual is online

What is Alagator?

- Scripting language for PDE's
- Parsed into an expression tree
- Assembled using FV / FE techniques
- Stored in hierarchical parameter data base

- Models are accessible, easily modified

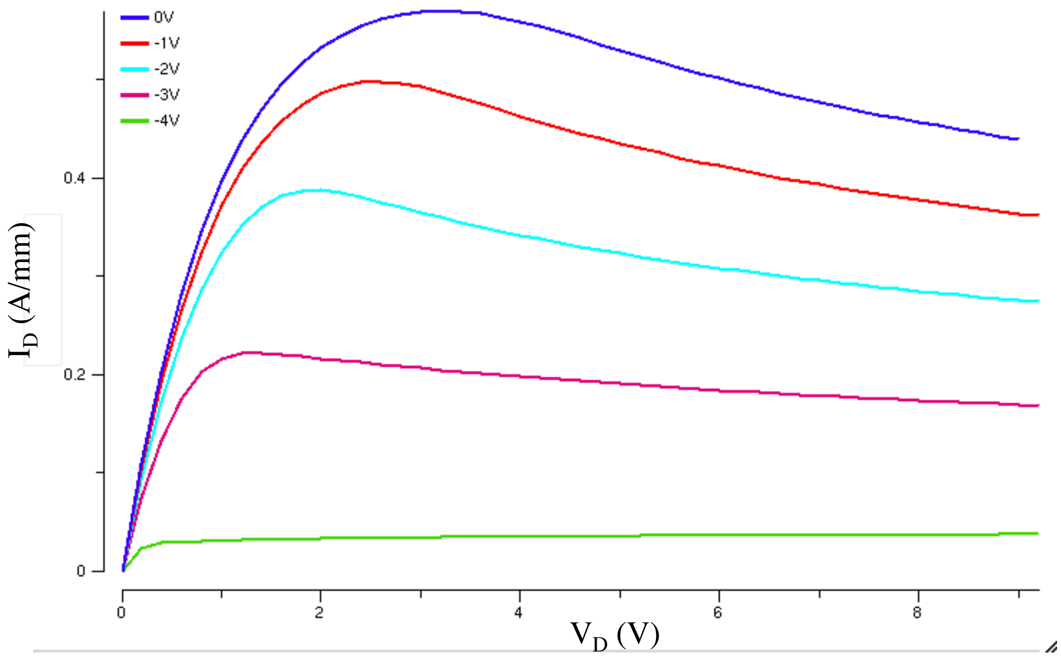
New HEMT Structure



[Not to scale]

- AlN and SiC successfully added
  - Fully functional, some parameters need tweaking
  - Traps/defects can be added to AlN
- T-shaped gate created for first time in FLOORS
  - Metal surrounded by oxide

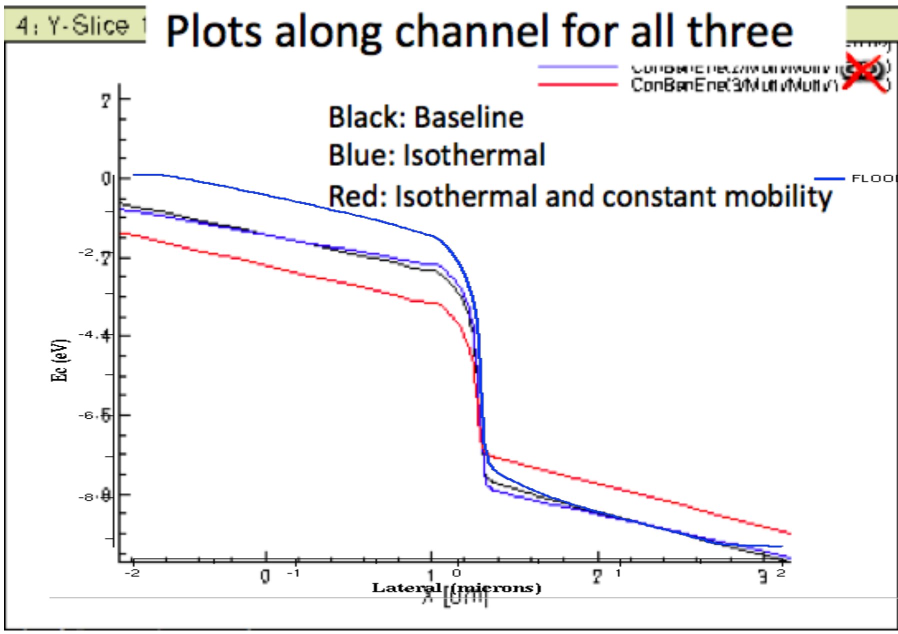
I_D vs. V_D Curves for Initial Model

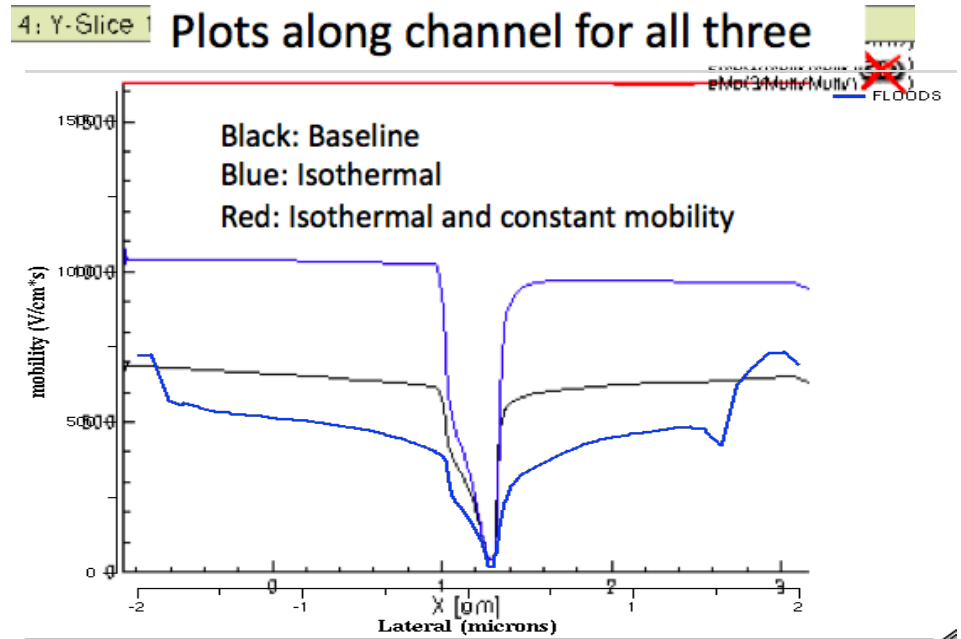


- Convergence and reasonable IV plot
  - T-gate, all materials, E_F, low and high field μ, temp-dependence for all parameters
- Ready to compare with Heller/SDevice and calibrate simulations

Parameter Comparison between SDevice and FLOORS

— FLOORS — SDevice





- E_C is good match, ~0.5 eV higher on left side of device

- Mobility is ~25% lower along most of channel

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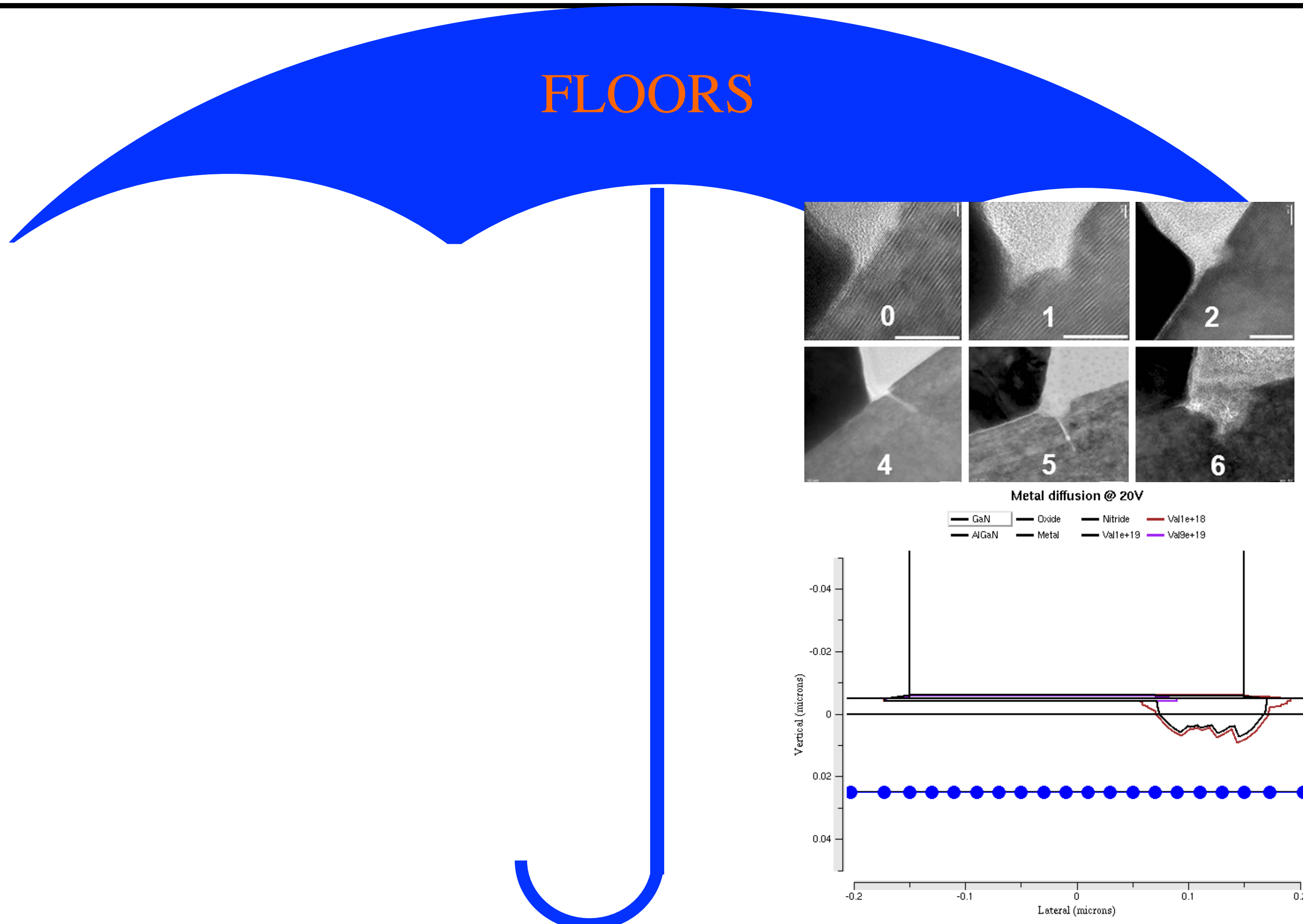
Simulation Approach



t=0, As Built

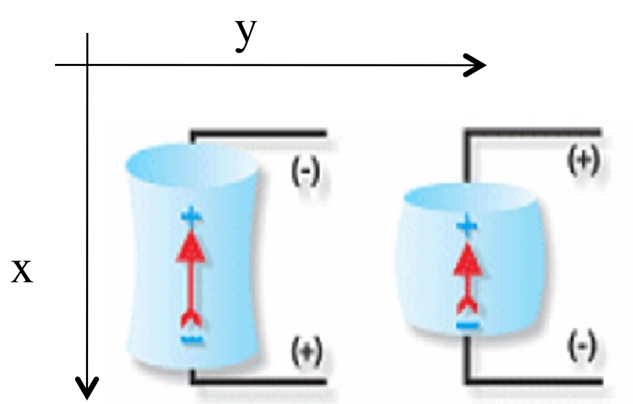
1] Park S.Y, Kim, M.J et al Microelectronics Reliability 49 2009 pp:478– 483

t>0, Degradation

Strain from Inverse Piezoelectric effect

1) Relationship (reduced to linear) between electric field, E and mechanical strain, ε: $\boldsymbol{\varepsilon_i = d_{ij} E_j}$ where j=1…3 and i=1….6

2) Assuming GaN crystal oriented such that polarization is vertical , $\varepsilon_{xx} = d_{33} E_x$, $\varepsilon_{yy} = d_{31} E_y$



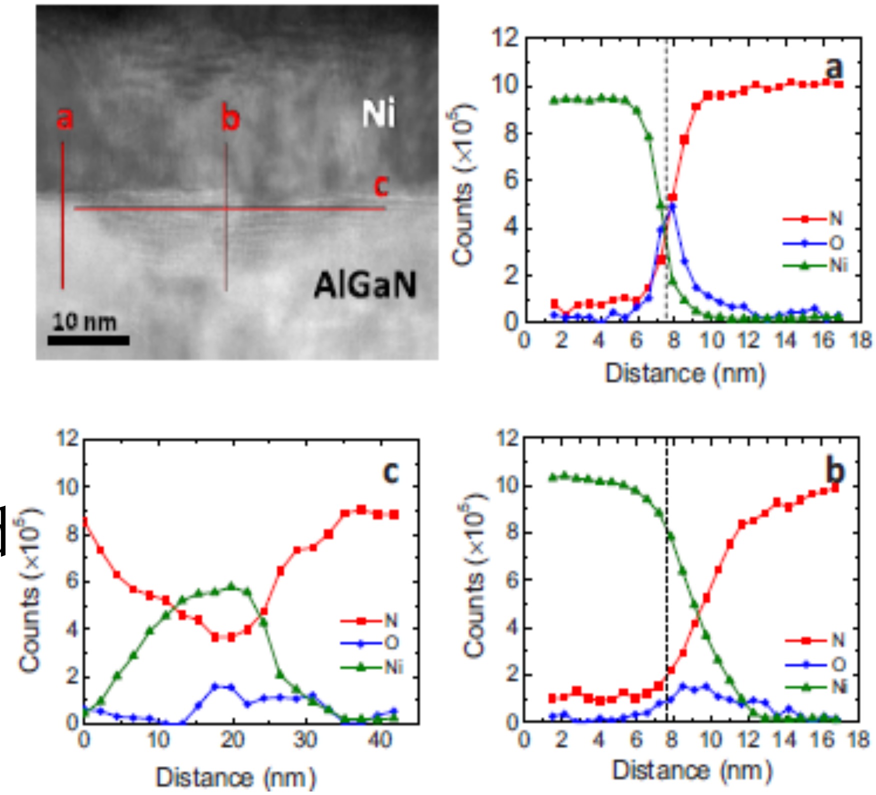
Assuming constant d_{33}, d_{13}, d_{15} resultant strains given by:

$$\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{pmatrix} = \begin{pmatrix} d_{33} & 0 \\ d_{31} & 0 \\ 0 & d_{15} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

GaN: d_{33} =3.4pm/V , d_{31} =-1.7pm/V , d_{15} =3.1pm/V

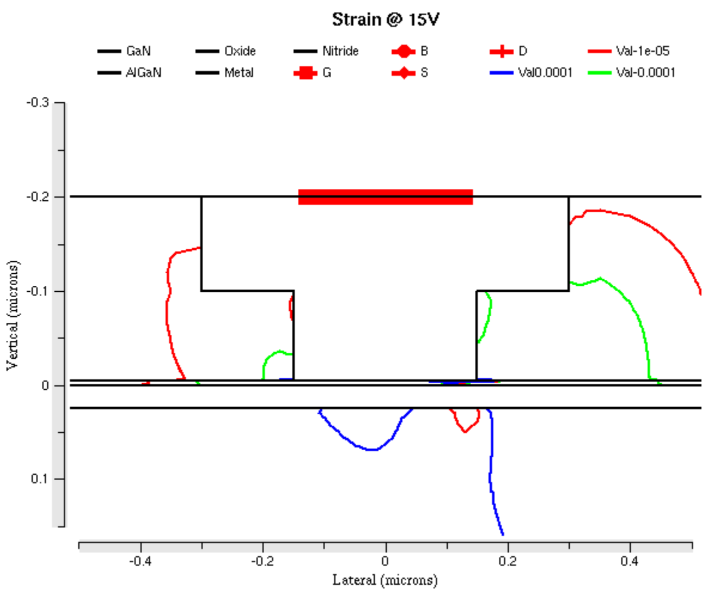
TEM images metal diffusion

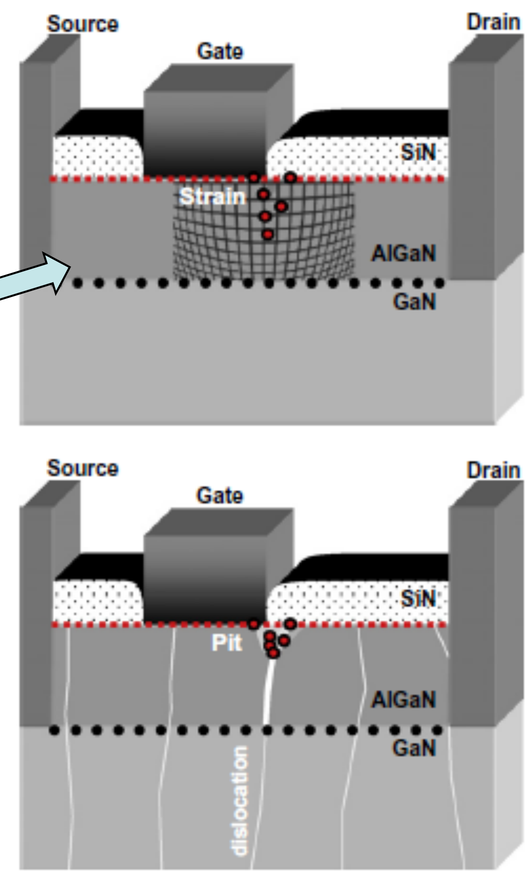
- Observed for Ni/Au gates commonly near edges
- Off-state, step-stressed
- EELS line scans show Ni diffusion into AlGaN



3] Ren, F et al. JVST B 5 Microelectronics and Nanometer structures Apr 2011

Strain distribution around T-gate





- Impurity diffusion driven by strain
- Pit formation suggests diffusion

3] Kuball, M et al Microelectronics Reliability 51 2011 pp:195– 200

Simulation Flowchart

Strain distribution within structure determined as a function of bias ⟹

$$\begin{pmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{xy} \end{pmatrix} = \begin{pmatrix} d_{33} & 0 \\ d_{31} & 0 \\ 0 & d_{15} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

⇩

Diffusion of metal impurity driven by strain ⟹

$$D' = D * exp\left(\frac{Q's}{kT}\right)$$

⇩

Metal impurity profile fed into Poisson's equation ⟹

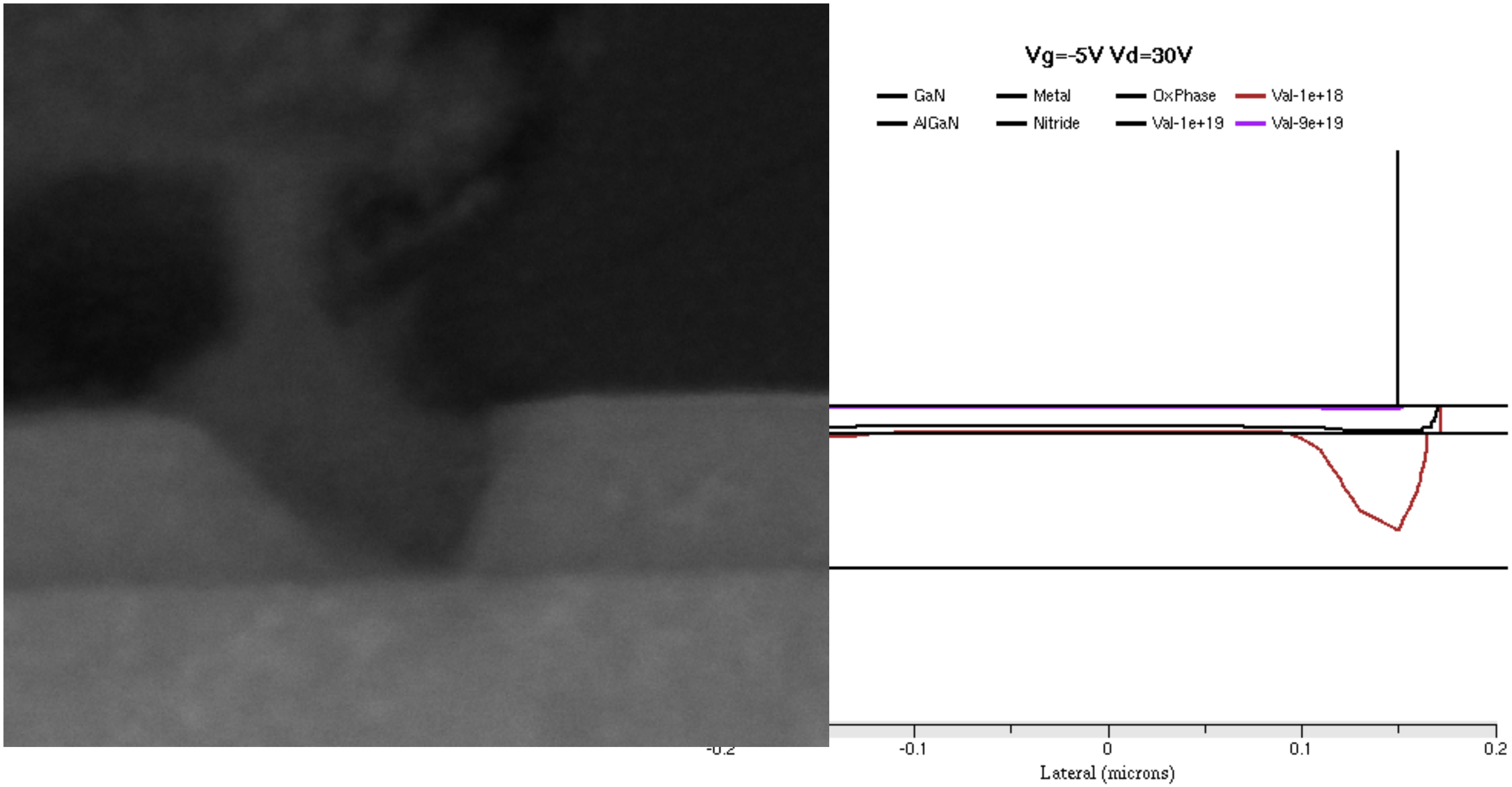
$$\frac{d^2\varphi(x)}{dx^2} = -\frac{\rho(x) + Impurity(x)}{\epsilon}$$

⇩

IV curves determined for each impurity profile ⟹

$$\frac{d(Elec)}{dt} = n * \mu_n * \frac{d^2 \emptyset(x)}{dx^2}$$

Physical Data vs. Simulation



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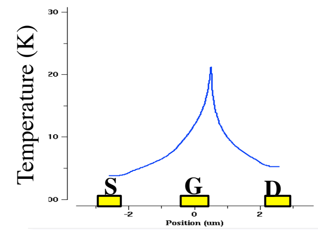
Discretization Methods



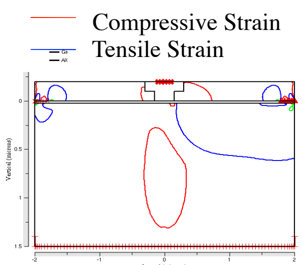
Electrical
(Finite Volume)

Electrical
(Finite Element)

Electro-Thermal
(Finite Element)

Electro-Mechanical
(Mixed)

FLOORS
(Finite Element)



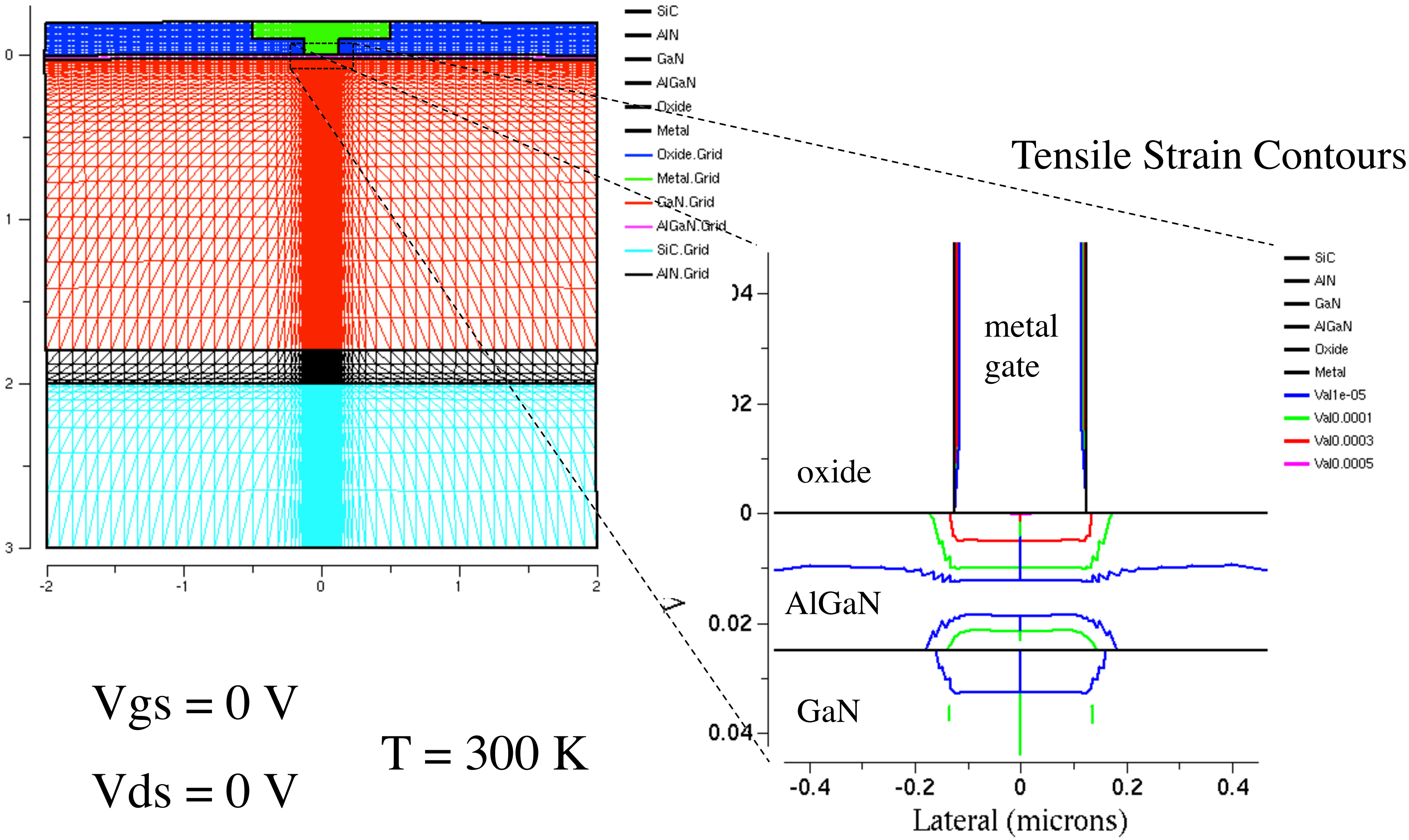
Thermal
(Finite Element)

Mechanical
(Finite Element)

Electro-Thermo-Mechanical Simulation

	Poisson's Eq.		Electron/Hole Continuity Eq.
Electro:	$\nabla^2 \Psi = -\frac{q}{\varepsilon}(p - n + N_D - N_A)$		$\frac{dn}{dt} = \frac{1}{q}\nabla \boldsymbol{J_n}$ $\boldsymbol{J_n} = -q\mu_n n \nabla \phi_n$
	Heat Eq.		
Thermo:	$c\frac{\partial \boldsymbol{T}}{\partial t} - \nabla \cdot K \nabla \boldsymbol{T} = Q$	where,	$Q = \boldsymbol{J_n}^2 \frac{1}{q\mu_n n}$
	Equilibrium Eq.		
Mechanical:	$\nabla \cdot \sigma + F = \rho \nabla^2 u$	where,	$\sigma = D\,(\epsilon - \epsilon_0)$ $\epsilon_0 = \nabla \Psi \cdot d_{pz}$ $D(\boldsymbol{T})$ function of temperature

Simulation Results on GaN HEMT - Baseline



Vgs = 0 V

Vds = 0 V

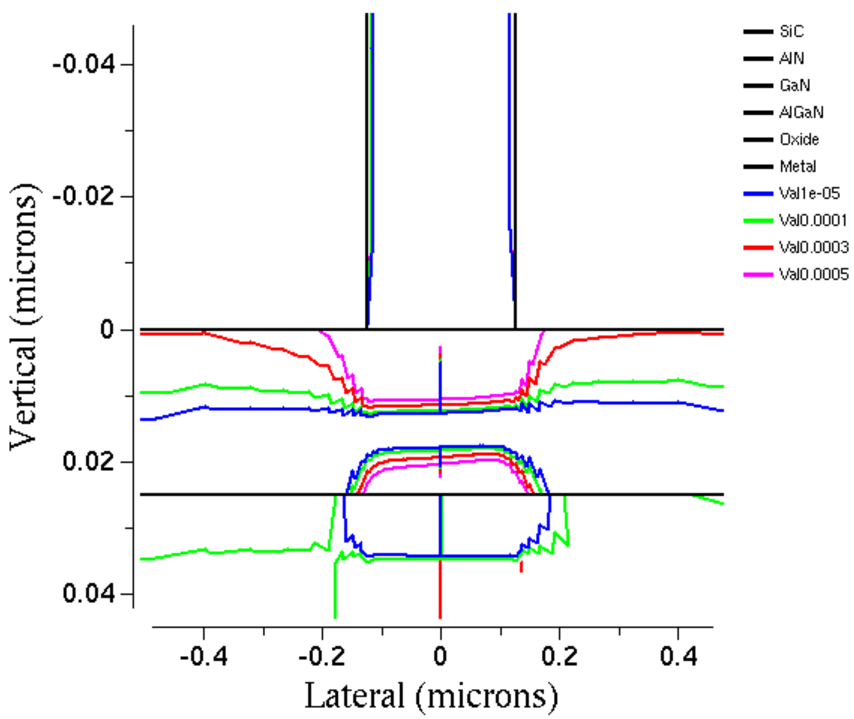
T = 300 K

Temp dependence on Young's Mod.

No temperature dependence on Young's modulus

Vgs = 0 V   Vds = 6.1 V

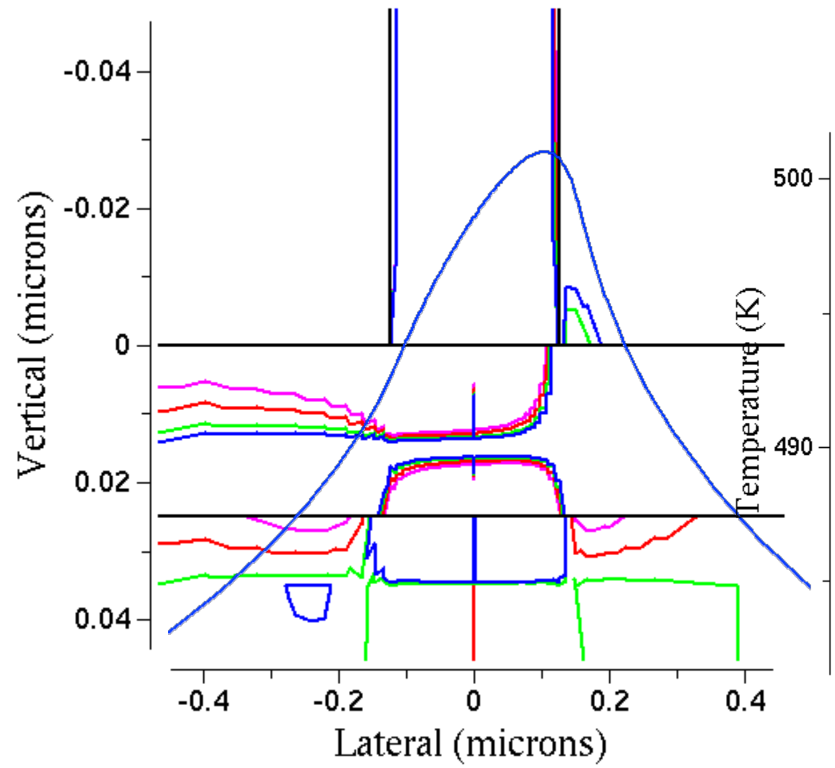
T(max) = 500 K



Temperature dependence on Young's modulus

Vgs = 0 V   Vds = 6.1 V

T(max) = 500 K



Incorporation of Compact Model for Gate Leakage

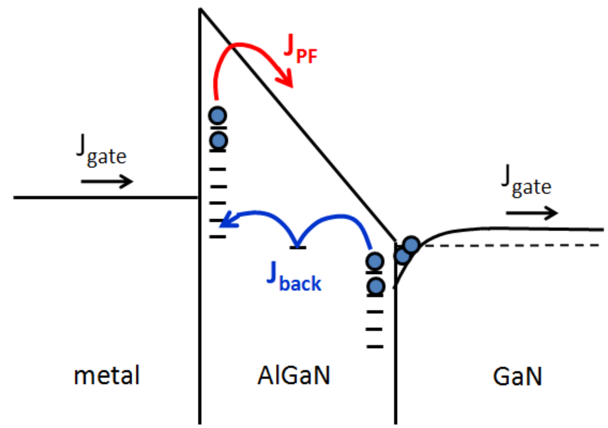
Poole-Frenkel Emission

- dominant leakage mechanism for near threshold gate biases

$$J_{PF} = CE\exp\left(-\frac{E_T - \Delta\phi_T}{rkT}\right)$$

$$\phi_T = \sqrt{\frac{q^3 E}{\pi\varepsilon_0\varepsilon_{AlGaN}}}$$

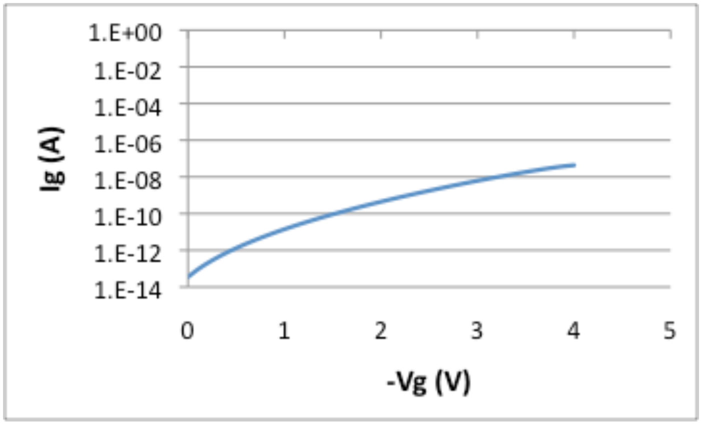
J. Frenkel, *Phys. Rev.*, vol. 54, p. 647, 1938.



Min Chu, Dissertation 2012

r=1.25
E_T=0.49 eV
C=7.3e-6 (1/Ωm)

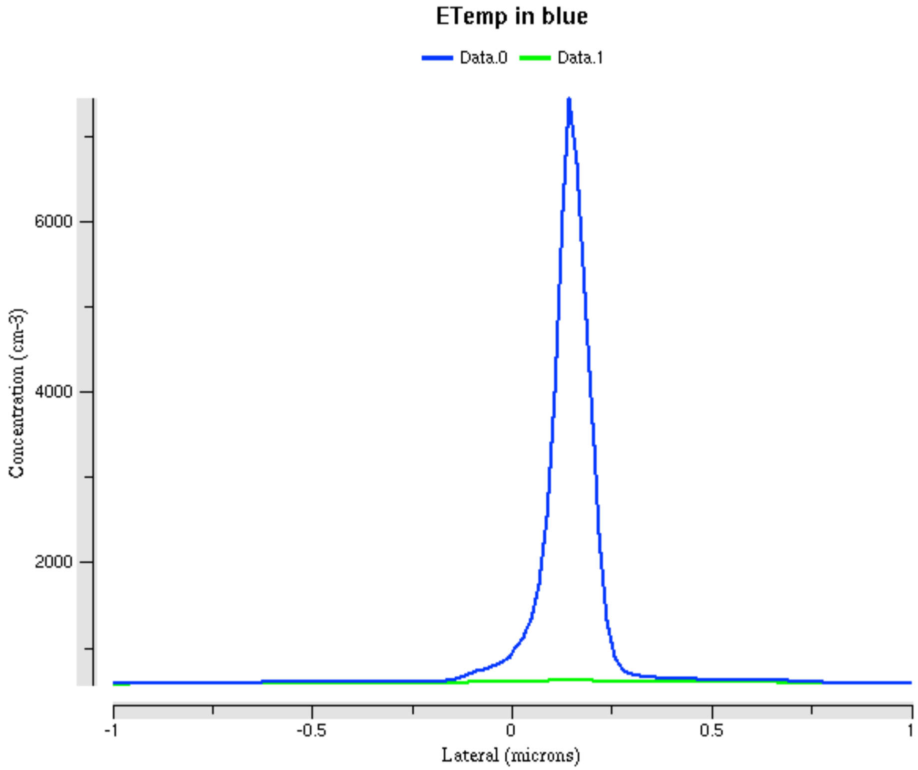
- parameters extracted from fit to Experimental data (Min Chu, 2012)

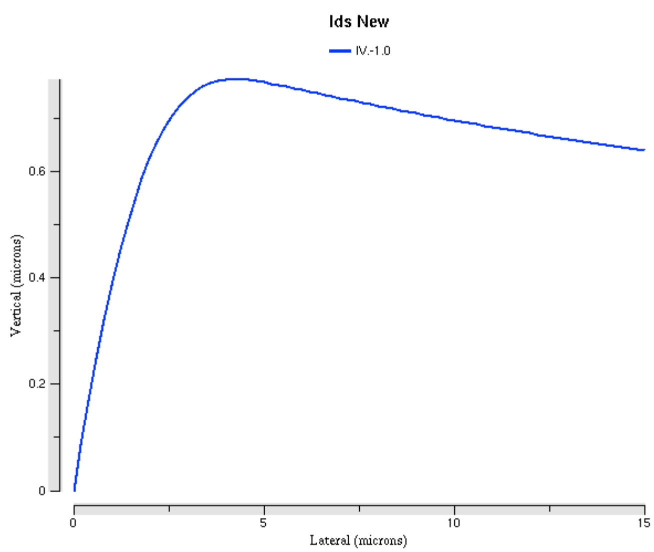


- P-F equation added to continuity eq. as a generation term
- simulated results are comparable to measured data

Electron Temperature

- Simulation of Electron Temperature
- Energy Balance
  - Carrier Heating
  - Energy Relaxation
- $V_{GS} = -1, V_{DS} = 15V$
- Temperature correlates well with Noise temperature results





Change Mobility Expressions to account for degradation

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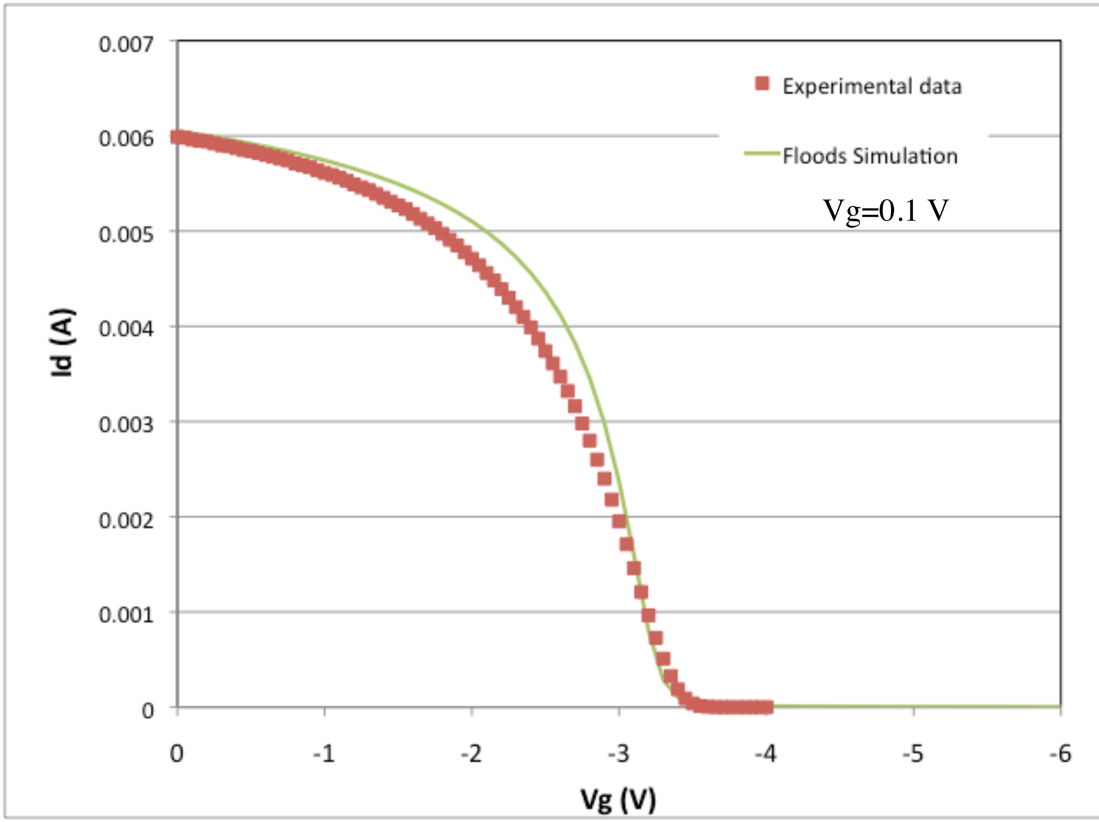
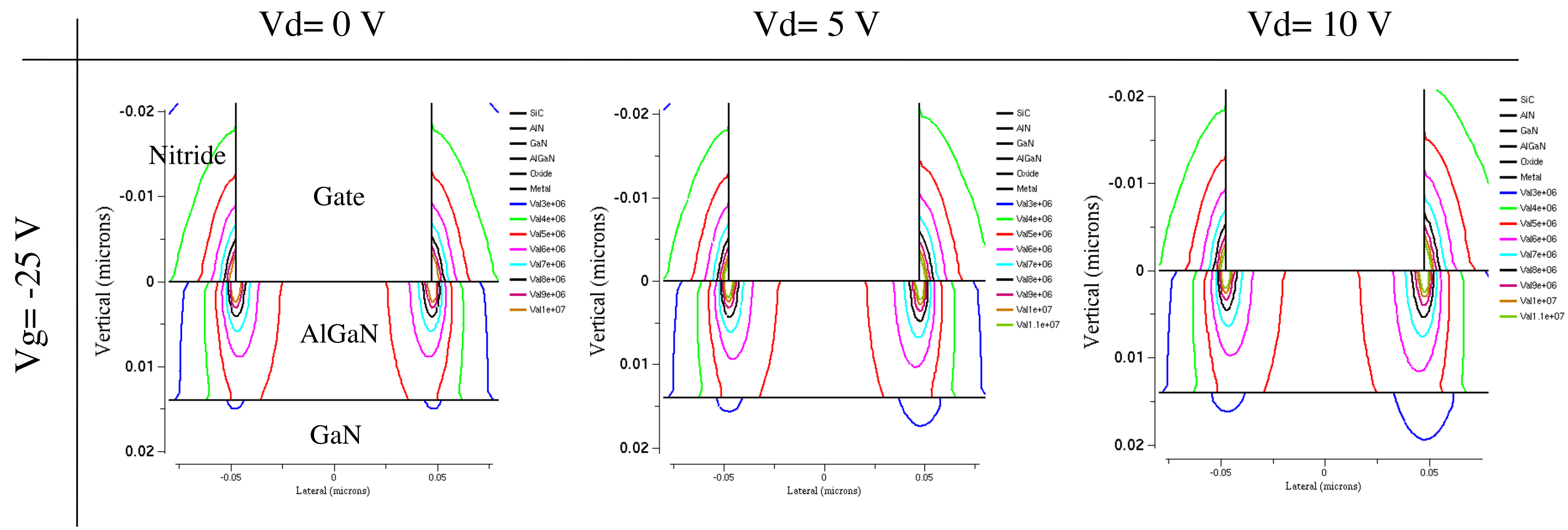
Simulation Calibration with Experimental Data



- Electrostatics are in good agreement

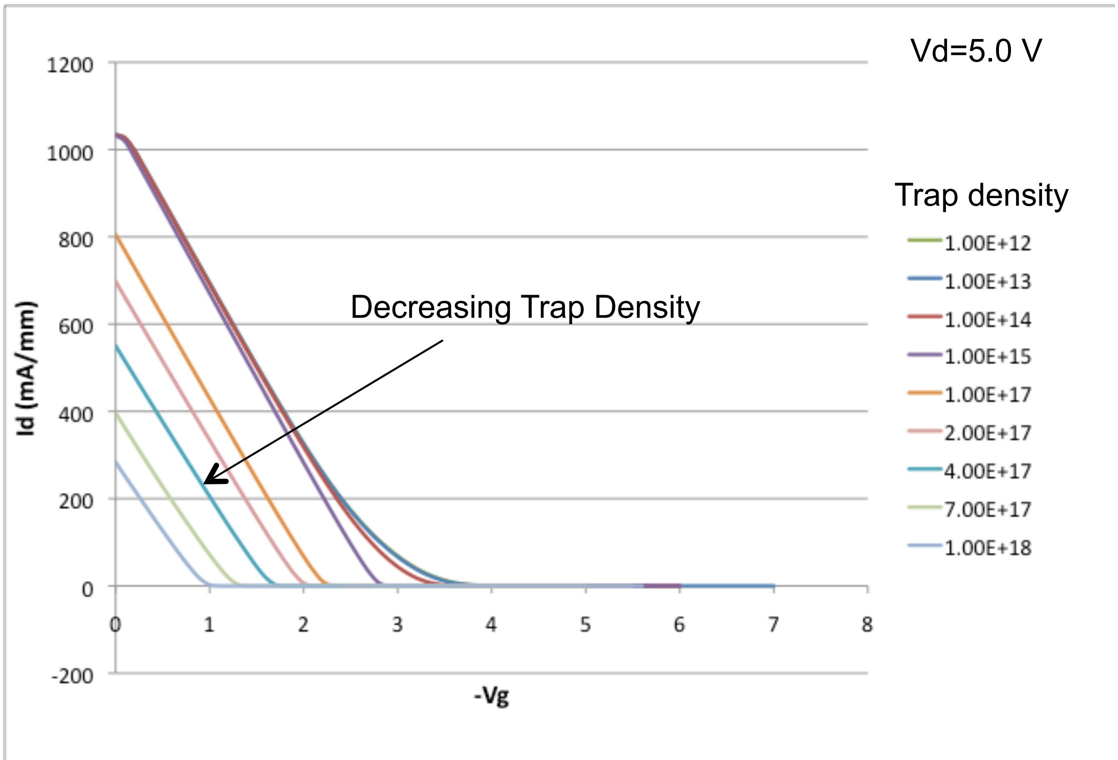
Exploration of E-field under various bias conditions

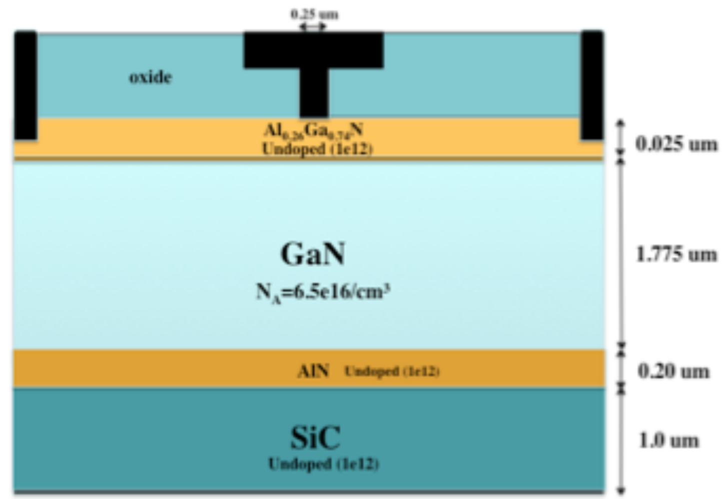
- To aid degradation study



Virtual gate effect due to trapped negative charges

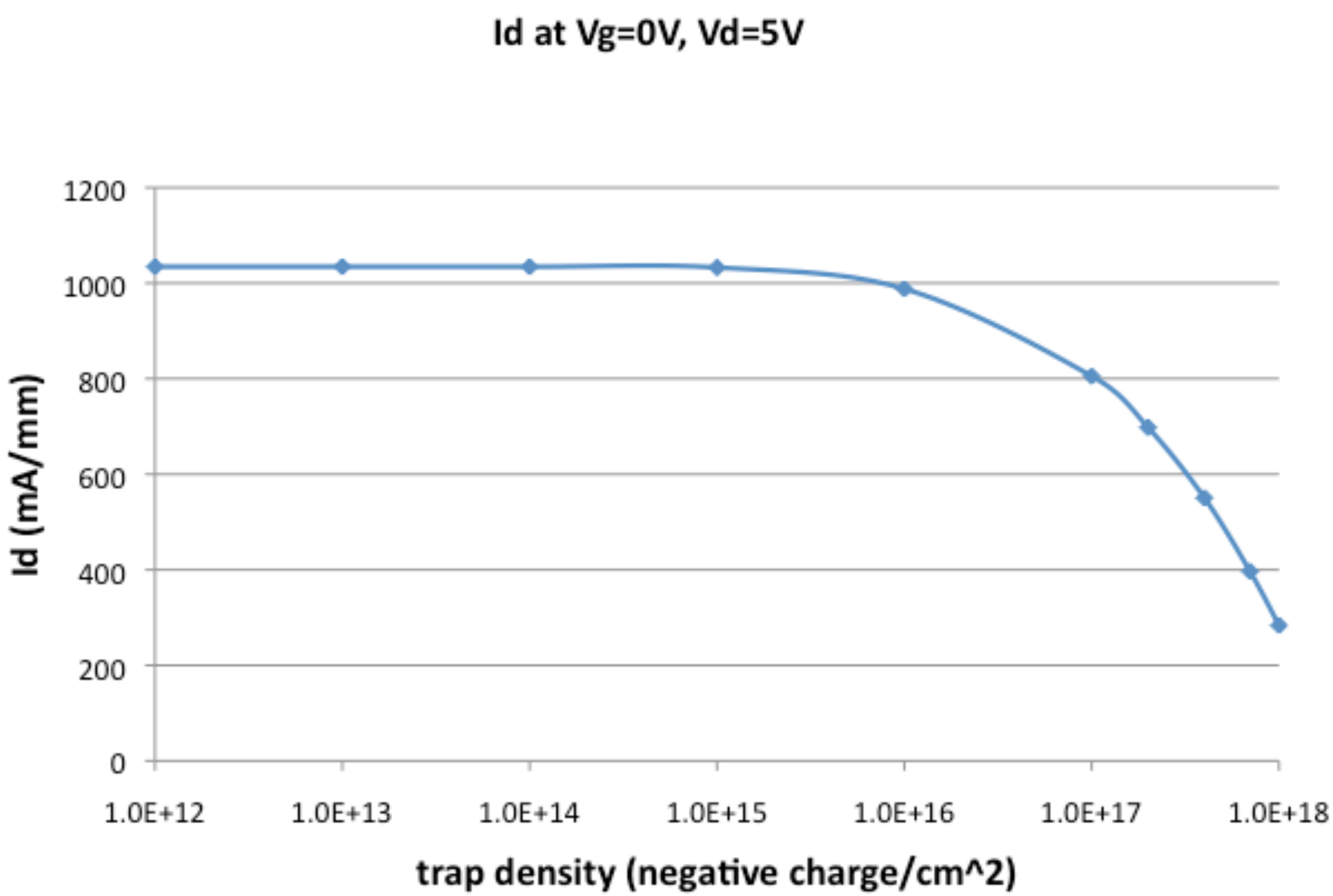
- Exploring possible influence of radiation induced charge trapping on threshold voltage and drain current





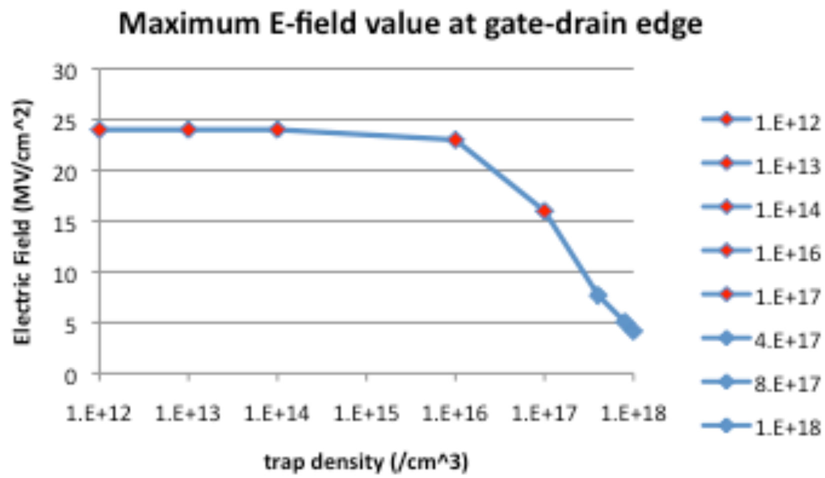
- Added uniform negative trapped charge density in AlGaN/GaN/AlN layers

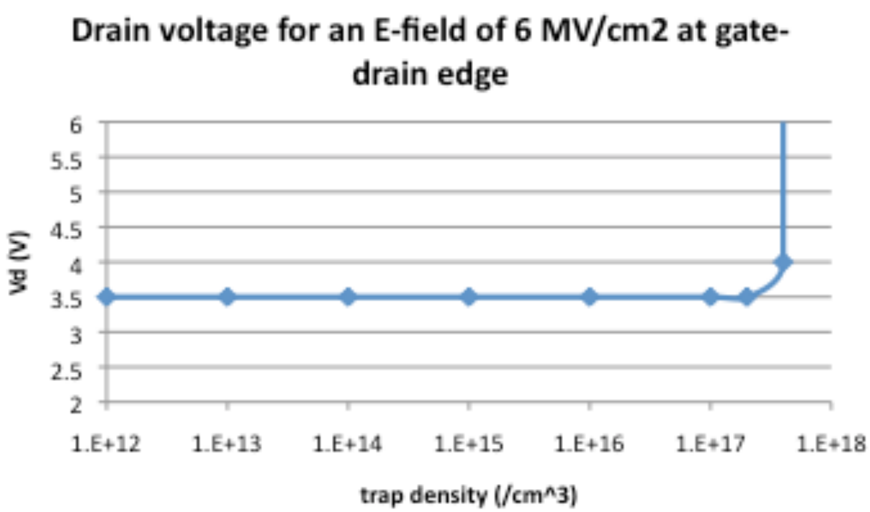
Virtual Gate Effect: I_d lowering



Virtual Gate Effect: E-field Lowering

Simulation Conditions:
V_g=-1V
V_s=0V
V_d=range (0-20 V)





*Red data points refer to projected values since simulation was not run to a sufficiently high drain voltage to get exact the value due to convergence issues.

Conclusions

- Off State Degradation
  - Effective Model that accounts for observed failures
  - Piezoelectric strain increase in diffusion
- On State Degradation
  - Multi-physics (Etemp, Ltemp, Strain)
  - Tunneling Models
  - Etemp should provide more accurate tunneling
- Proton Effects
  - Good correlation with experimental work
  - Show decrease in field strength